# Unsaturated hydraulic properties of vegetated soil under single and mixed planting conditions

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TECHNICAL NOTE

# Unsaturated hydraulic properties of vegetated soil under single and mixed planting conditions

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Effects of plant roots on changes of soil hydraulic properties, including soil water retention curves (SWRC) and soil hydraulic conductivity functions (SHCF), are not well understood, especially when soil is unsaturated and vegetated with multiple plant species. The aim of this note is to quantify the root effects on both SWRC and SHCF of silty sand using the instantaneous profile method. Four types of vegetated soil, namely bare, grass-only, tree-only and mixed tree–grass silty sand, were subjected to a controlled drying–wetting cycle in a plant room. Plant roots affect the air-entry value, saturated hydraulic conductivity and reduction rate of unsaturated hydraulic conductivity (with respect to suction) most significantly, but the roots do not affect the reduction rate of volumetric water content much. When planted with single species (grass or tree), the air-entry value of silty sand increased, while the saturated hydraulic conductivity and reduction rate of unsaturated hydraulic conductivity with suction decreased. However, under the mixed planting conditions, opposite results are found.

KEYWORDS: partial saturation; seepage; suction; vegetation; water flow

## INTRODUCTION

Vegetation is known to affect the hydrology and hence slope stability (Osman & Barakbah, 2011; Smethurst *et al.*, 2015). Plant roots cause changes in soil matric suction (Simon & Collison, 2002; Veylon *et al.*, 2015; Ng *et al.*, 2016a, 2018; Ni *et al.*, 2017) through evapotranspiration and soil hydraulic properties, including the soil water retention curve (SWRC) and the soil hydraulic conductivity function (SHCF). Some studies (Table 1) have shown an increase in water retention capability when plant roots are present in the soil (Scanlan & Hinz, 2010; Rahardjo *et al.*, 2014; Leung *et al.*, 2015; Ng *et al.*, 2016a, 2016b; Jotisankasa & Sirirattanachat, 2017), probably because of the blockage of soil pore space by roots (Buczko *et al.*, 2007). However, some studies have reported an opposite result (Ng *et al.*, 2016a; Jotisankasa & Sirirattanachat, 2017), arguably because of the formation of soil cracks due to, for instance, repeated soil shrinkage/swelling and root decay/growth (Vergani & Graf, 2015; Ng *et al.*, 2016a; Ni *et al.*, 2017; Leung *et al.*, 2018).

There is a dearth of test data about the effects of plant roots on the SHCF (Table 2). Jotisankasa & Sirirattanachat (2017) show that root effects on hydraulic conductivity were prominent only when matric suction of the soil was less than 10 kPa, whereas the hydraulic conductivity measured by Song *et al.* (2017) found that roots affect unsaturated hydraulic conductivity for the entire suction range considered (<100 kPa). Thus, the presence of plant roots does not necessarily always reduce or increase unsaturated hydraulic conductivity, depending both on the plant and soil types. Indeed, although Rahardjo *et al.* (2014) and Jotisankasa & Sirirattanachat (2017) tested the same grass type, the soil hydraulic properties of the vegetated soils measured were different, possibly because of the different soil types considered in these two studies. Moreover, there has been no study that investigates the effects of multiple plant functional groups (i.e. mixed planting of herbaceous and woody species) on both the SWRC and SHCF (Tables 1 and 2).

The aim of this study is to investigate the unsaturated hydraulic properties of soil with four different vegetation conditions (i.e. bare, grass-only, tree-only and mixed tree–grass planting). Replications of instrumented soil columns were subjected to a controlled drying/wetting cycle, the results of which were used to determine the root effects on the SWRC and SHCF by way of the instantaneous profile method. Any plant-induced changes in the two soil hydraulic properties were interpreted with plant root traits.

## MATERIALS AND METHODS

### *Soil*

Completely decomposed granite (CDG; silty sand, SM) was used for testing. At a dry density of 1777 kg/m$^3$ (the compaction level considered in this study), the saturated hydraulic conductivity, $k_s$, of the CDG was $1{\cdot}4 \times 10^{-6}$ m/s. The other index properties are summarised in Table 3.

### *Plants*

A tree (*Schefflera heptaphylla*; ivy tree) and a grass (*Cynodon dactylon*; Bermuda grass) species were selected for testing. These species are ecologically suitable for slope rehabilitation and restoration in many parts of Asia (GEO, 2011). Before transplantation, tree individuals with shoot

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**Table 1. Summary of existing studies on the effects of plants on SWRC**

| Plant species | Soil type | Dry density: $Mg/m^3$ | Observed plant effects | Reference |
|---|---|---|---|---|
| Orange jasmine (*Murraya paniculata*); vetiver grass (*Chrysopgon zizanioides*) | Poorly graded sand (SP) | 1·31 | Water retention capacity increased in both vegetated soils | Rahardjo *et al.* (2014) |
| Ivy tree (*Schefflera heptaphylla*) | Silty sand (SM) | 1·49 | Vegetated soil has higher air-entry value (AEV) but similar desorption rate, compared with bare soil | Leung *et al.* (2015) |
| Ivy tree (*Schefflera heptaphylla*) | Silty sand (SM) | 1·78 | Water retention capacity increased at intermediate (e.g. 120 mm) and wide plant spacing (e.g. 180 mm), but it reduced at close plant spacing (e.g. 60 mm). | Ng *et al.* (2016a) |
| Vetiver grass (*Chrysopgon zizanioides*) | Low-plasticity silt (ML) | 1·31 | AEV increased with root biomass but then decreased after a certain threshold root biomass | Jotisankasa & Sirirattanachat (2017) |

**Table 2. Summary of existing studies on the effects of plants on SHCF**

| Plant species | Soil type | Dry density: $Mg/m^3$ | Observed plant effects | Reference |
|---|---|---|---|---|
| Vetiver grass (*Chrysopgon zizanioides*) | Low-plasticity silt (ML) | 1·31 | Root induced changes in SHCF are mainly within low matric suction range (less than 10 kPa) | Jotisankasa & Sirirattanachat (2017) |
| Bermuda grass (*Cynadon dactylon*); Vetiver grass (*Chrysopgon zizanioides*) | Lean clay (CL) | 1·38 | Unsaturated hydraulic conductivity of soil vegetated with either Bermuda or vetiver grass is higher than that of bare soil at any given suction | Song *et al.* (2017) |

**Table 3. Index properties of completely decomposed granite (CDG)**

| Index properties | Value |
|---|---|
| Standard compaction tests | |
| Maximum dry density: $kg/m^3$ | 1870 |
| Optimum moisture content: % | 12 |
| Particle-size distribution | |
| Gravel content (>2 mm): % | 19 |
| Sand content (≤2 mm): % | 42 |
| Silt content (≤63 μm): % | 27 |
| Clay content (≤2 μm): % | 12 |
| Specific gravity | 2·60 |
| Atterberg limit | |
| Plastic limit: % | 26 |
| Liquid limit: % | 44 |
| Plasticity index: % | 18 |
| *Saturated hydraulic conductivity, $k_s$ | |
| Bare: m/s | $1{\cdot}4 \times 10^{-6}$ |
| Grass-only soil: m/s | $(4{\cdot}2 \pm 0{\cdot}8) \times 10^{-7}$ |
| Tree-only soil: m/s | $(3{\cdot}3 \pm 0{\cdot}6) \times 10^{-7}$ |
| Mixed tree–grass soil: m/s | $(9{\cdot}6 \pm 1{\cdot}1) \times 10^{-6}$ |
| †Unified Soil Classification System (USCS) | Silty sand (SM) |

*According to falling-head hydraulic conductivity test outlined in ASTM (2010b).
†According to Unified Soil Classification System (USCS; ASTM, 2010a).

length of 800 ± 35 mm (mean ± standard error of mean) and root depth of 140 ± 15 mm were provided by Tung Kee Garden Horticulture Ltd in Hong Kong. Grass turf with shoot length of 50 ± 12 mm and root depth of 40 ± 14 mm was used for testing.

After transplantation, the plants were left to grow for 4 months in a plant room (relative humidity 60 ± 5%, air temperature 25 ± 1°C, radiant energy 120 ($\mu mol/m^2$)/s) to facilitate plant growth (Ng *et al.*, 2016a). During the growing period, all bare and planted columns were irrigated every 3 days so that the soil moisture content was close to the field capacity of the CDG (20–22% by mass).

*Test set-up and instrumentation*

Soil columns (400 mm high and 200 mm dia.; Fig. 1) were constructed for this study. The CDG was compacted to the column up to a depth of 350 mm at a dry density of 1777 $kg/m^3$. Drainage holes were made at the bottom of each column for free drainage. In total, nine planted columns were constructed, three for the tree-only cover, three for the grass-only cover and three for the mixed tree–grass plantation. One bare column was used as control.

A vertical array of miniature-tip tensiometers (2100 F, Soil Moisture Equipment Cooperation) was installed in each column to measure negative pore water pressure or matric suction of the soil (Fig. 1). At the same instrument depths, an array of four calibrated soil moisture probes (SM 300, Delta-T Device Ltd) was installed to measure the soil volumetric water content (VWC).

*Test procedures*

After 4 months of growing, the surface of all planted and bare columns were ponded with water until basal percolation was observed and suction at all instrumented depths became zero. Then, all columns were left in the plant room for evapotranspiration for 6 days (referred to as the drying test). Subsequently, the ten columns were ponded again, but with a controlled constant water head of 20 mm for 2 h using a Mariotte's bottle (referred to as the wetting test). During both the drying and wetting tests, the bottom holes of each column remained open for free drainage. Responses of suction, VWC and any basal percolation were recorded continuously.

After testing, root traits including root volume and root depth were measured from each planted column, following

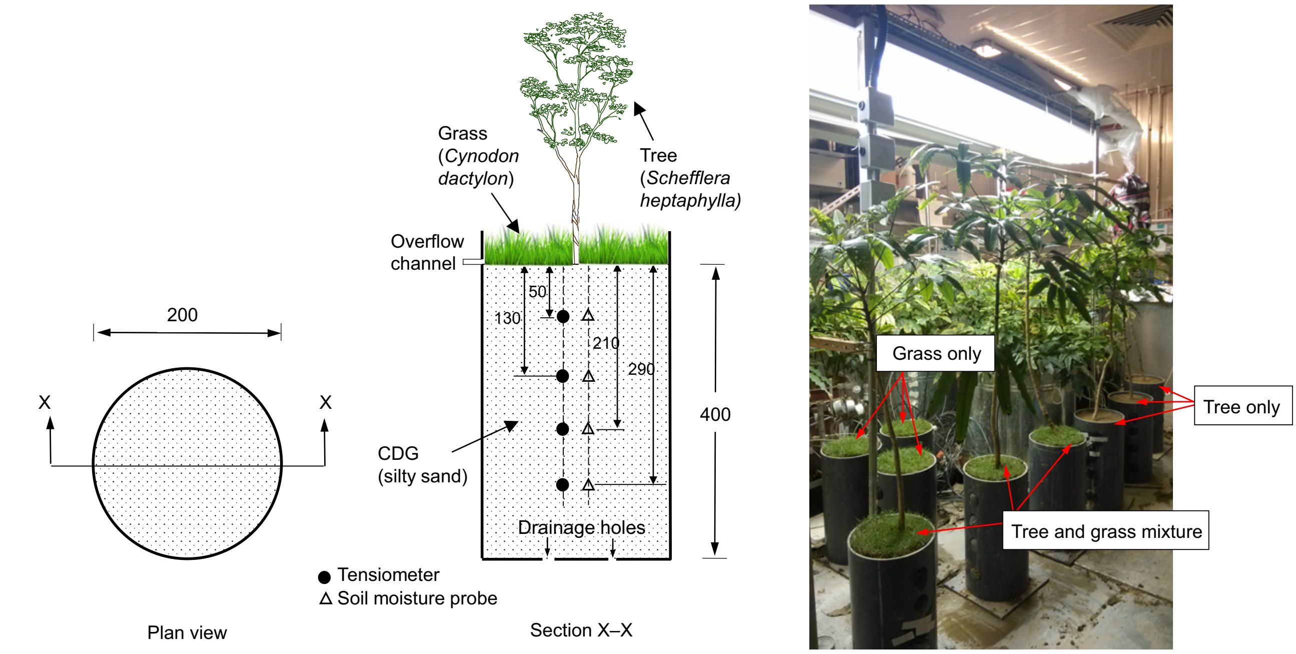


**Fig. 1. Schematic diagram and overview of the planted soil columns. All units expressed in mm**

the procedures described by Reubens (2010). The root volume ratio, $R_v$, was obtained by normalising the measured root volume by the soil volume of that depth range.

*Interpretation methods*

The SWRC of each column was obtained by relating the measured suction and VWC at the same instrument depth. The VWC of each SWRC was divided by the soil porosity to obtain the degree of saturation, assuming that there is no soil volume change upon drying and wetting processes. Indeed, element tests performed by both Chiu & Ng (2012) and Leung & Ng (2016) show that CDG compacted to a similarly high dry density to that of the present study has negligible volume change when suction is less than 100 kPa. Moreover, there was no observed collapse during the first wetting. Each SWRC was fitted by the equation proposed by van Genuchten (1980)

$$S_r = \left[1 + \left(\frac{s}{a}\right)^n\right]^{-m} \tag{1}$$

where $S_r$ is the soil's degree of saturation; $s$ is matric suction; $a$ is related to the air-entry value (AEV); $n$ and $m$ control the shape of an SWRC.

The SHCF of each column was determined by the instantaneous profile method (Watson, 1966; Ng & Leung, 2012; Leung *et al.*, 2016). The measured SHCF was then compared with the equation proposed by van Genuchten (1980)

$$k_r = S_r^{0\cdot 5}[1 - (1 - S_r^{1/m})^m]^2 \tag{2}$$

where $k_r$ is the relative soil hydraulic conductivity, which is the ratio between soil hydraulic conductivity $k$ and saturated hydraulic conductivity $k_s$.

The $k_s$ value of each vegetated case was determined by back-analysing the suction data obtained during the wetting phase of each test using the numerical model developed by Shao *et al.* (2017). The $k_s$ values are summarised in Table 3.

Statistical analysis was performed using Microsoft Excel. Significant differences were assessed with one-way ANOVA (analysis of variance), followed by post hoc Fisher's least-significant-difference test. Results were considered statistically significant when $p$-value $\leq 0{\cdot}05$. Different letters (i.e. a, b, c and d) were used to indicate statistical significance of differences among groups when the $p$-value is $\leq 0{\cdot}05$. This means that when any two groups (e.g. suction in bare and grass-only soil) have the same letter, they have no statistical difference. On the contrary, when they have different letters, the groups are significantly different statistically.

## RESULTS AND DISCUSSION

*Plant root traits*

Figure 2 shows the $R_v$ distributions with depth for grass-only, tree-only and mixed grass–tree cases, respectively. The $R_v$ value of grass roots distributed almost linearly along the depth, peaked at the soil surface. The trees have a parabolic distribution of $R_v$, with the maximum $R_v$ located approximately at the mid-depth of their root zone. The peak $R_v$ of trees was almost 70% larger than that of grass in both single and mixed planting conditions. In the top 85 mm, the $R_v$ of trees is statistically significantly higher than that of grasses ($p$-value $<0{\cdot}01$). Whether the trees and grasses were planted

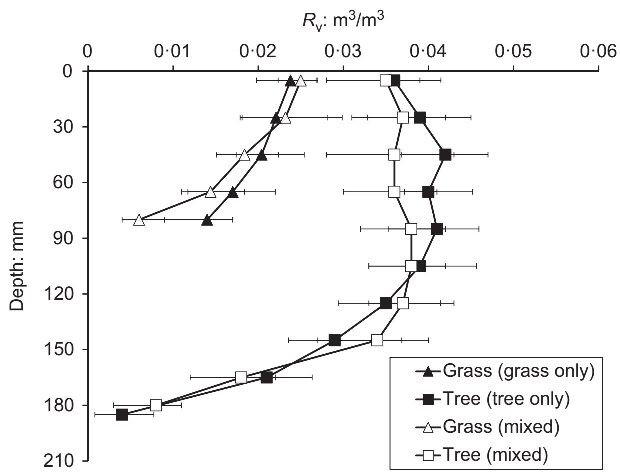


**Fig. 2. Distributions of root volume ratio under different vegetated conditions**

individually or together (i.e. mixed plantation) has minimal effects on the $R_v$ (Fig. 2).

When grown in relatively coarse soil (e.g. the silty sand tested in this study), plant roots tend to grow laterally to explore a greater soil volume for resources such as water and nutrients (Hamer *et al.*, 2016). On the contrary, due to the relatively poor aeration and low hydraulic conductivity in fine-grained soil, root growth would be more restricted and localised (Travlos & Karamanos, 2006).

*Soil water retention curves*

Figure 3(a) shows the measured and fitted drying SWRCs of the bare, grass-only and tree-only soils. The SWRCs of grass-only and tree-only soils are similar to each other (Table 4), and the amount of VWC retained for a given suction in these vegetated cases is statistically higher than that of the bare soil ($p$-value $<0{\cdot}001$). Although the parameter $n$ which describes the desorption rate of SWRC is similar between the bare and vegetated soils, the parameter $a$ (which controls AEV) of both vegetated soils is noticeably lower than that of the bare case. This is consistent with the models proposed by Scanlan & Hinz (2010) and Ng *et al.* (2016b), who hypothesise that root occupancy in the pore space of coarse-grained soil would reduce the soil pore diameter, causing an increase in matric suction according to the capillary law. Indeed, the root diameter range, for both grasses and trees, is 0·15–2 mm. Recalling the capillary law and for a given surface tension, this diameter range affects the soil pore space that corresponds to a low range of matric suction (no more than 2 kPa). However, for fine-grained soil with clay content >12%, there are many factors possibly affecting the soil hydraulic properties, such as the release of organic matter as root exudates in the rhizosphere (Helliwell *et al.*, 2014), soil aggregation due to plant–bacteria interaction in soil (Horn & Smucker, 2005) and/or the formation of microcracks/fissures associated with the continual drying–wetting process due to root water uptake (Daly *et al.*, 2015).

The SWRCs of tree-only soils reported by Ng *et al.* (2016a) are superimposed in Fig. 3(b). They tested the same tree species and soil type as the present study and obtained the SWRC from soil that was planted with multiple trees with different spacings (60 and 180 mm; namely, test S60 and S180). When the tree spacing was wide, the SWRC was similar to that of single tree-only soil in the present study (Table 4). This is because the tree spacing is wide enough that the growth and water uptake action from each tree individual were not affected by the neighbouring trees (Ng *et al.*, 2016a). For closer tree spacing, the water retention capability reduced as compared to the bare soil. The SWRC of this close tree spacing case is similar to the one obtained under the mixed planting condition in this study. In both instances, root decay is observed due to interspecies (tree–grass) competition and intra-species (tree–tree) competition. This may have created soil macro-pores (Ghestem *et al.*, 2011), causing not only an increase in saturated hydraulic conductivity but also a reduction of water-holding capacity.

*Unsaturated soil hydraulic conductivity*

Figure 4(a) compares the relative drying SHCFs, $k_r$ (i.e. normalised by $k_s$ of the respective case). Each SHCF is obtained at 50 mm depth within the root zone, so any

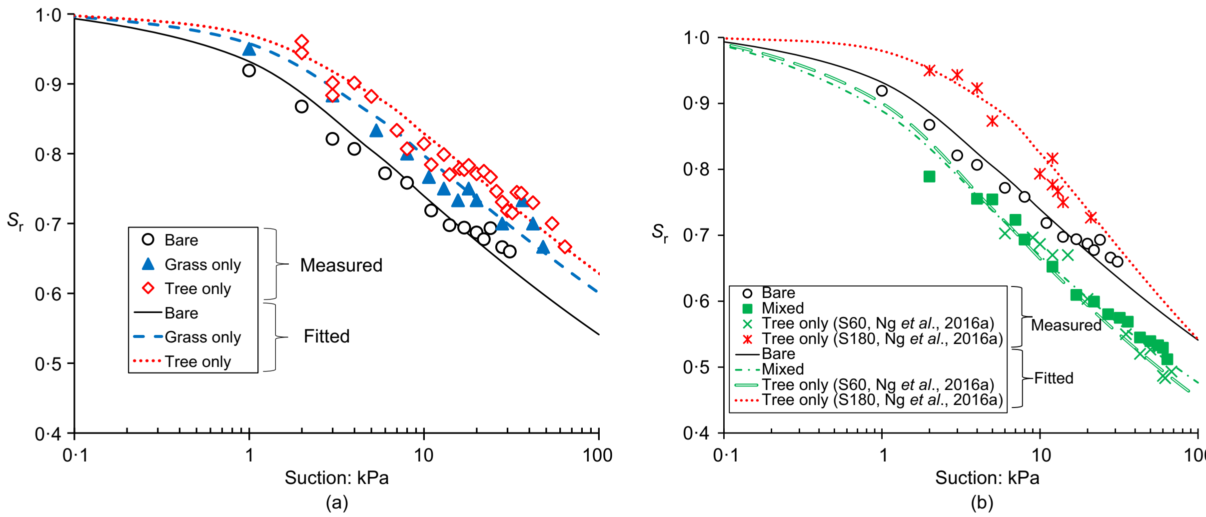


**Fig. 3. Measured and fitted SWRCs of (a) bare, grass-only and tree-only soils and (b) mixed tree–grass soil together with the data from Ng *et al.* (2016a) for a tree-only soil**

**Table 4. Statistical testing of the fitting parameters of SWRC using van Genuchten (1980) equation for the four vegetated conditions examined in this study and data from Ng *et al.* (2016a)**

| Test | $a$ | $n$ | $m$ |
|---|---|---|---|
| Bare (this study) | 8 ± 1·0c | 1·14 ± 0·01a | 0·12 ± 0·01a |
| Grass only (this study) | 5 ± 1·0b | 1·13 ± 0·02a | 0·12 ± 0·02a |
| Tree only (this study) | 3·5 ± 0·5ab | 1·13 ± 0·01a | 0·12 ± 0·01a |
| Mixed planting (this study) | 13·0 ± 1·4d | 1·15 ± 0·03a | 0·13 ± 0·02a |
| S60 (Ng *et al.*, 2016a) | 12·1 ± 1·5d | 1·16 ± 0·03a | 0·15 ± 0·02a |
| S180 (Ng *et al.*, 2016a) | 1·8 ± 0·4a | 1·17 ± 0·02a | 0·14 ± 0·01a |
| $p$-value | <0·001 | 0·384 | 0·462 |

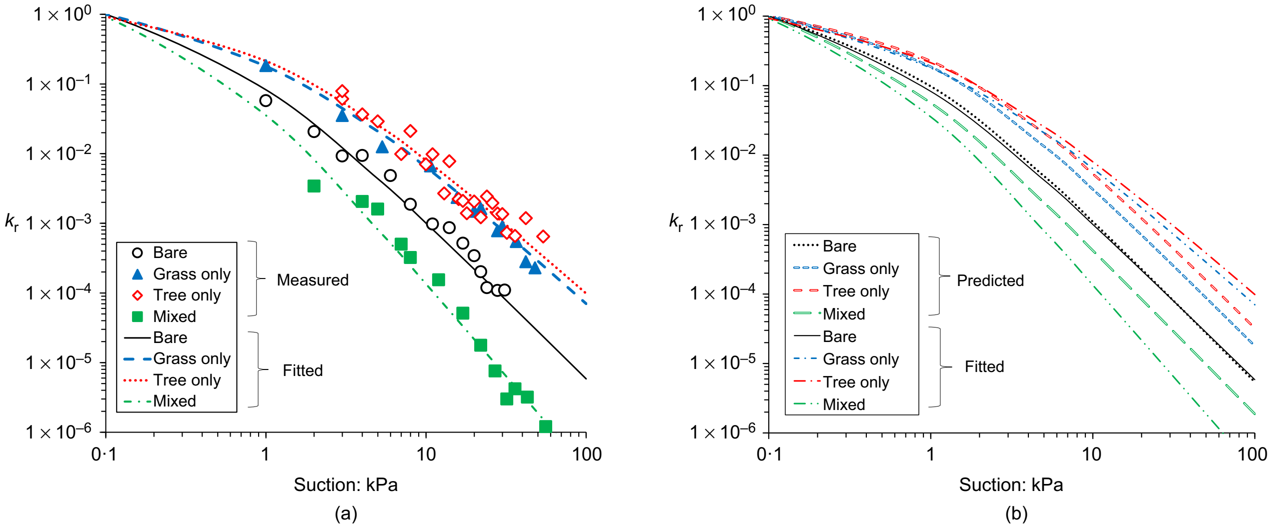


**Fig. 4. Comparisons between (a) measured and best-fitted SHCF and (b) fitted and predicted SHCF of the four vegetated conditions**

**Table 5. Statistical testing of the fitting parameters of SHCF using van Genuchten (1980) equation**

| Test | *a* | *n* | *m* |
|---|---|---|---|
| Bare (this study) | 8 ± 1·0c | 1·13 ± 0·01c | 0·12 ± 0·02b |
| Grass only (this study) | 5 ± 1·0ab | 1·03 ± 0·01ab | 0·03 ± 0·01a |
| Tree only (this study) | 3·5 ± 0·5a | 1·01 ± 0·01a | 0·01 ± 0·002a |
| Mixed planting (this study) | 13 ± 1·4d | 1·27 ± 0·03d | 0·2 ± 0·02c |
| *p*-value | <0·001 | <0·001 | <0·001 |

root effects can be investigated. Both Fig. 4(a) and Table 5 show that the reduction rate of $k_r$ with respect to an increase in suction (characterised by the parameter *n*), decreased in grass- and tree-only cases, but increased in the mixed-species cases ($p$-value <0·001). This means that the presence of plant roots, depending on the plant types and planting method (i.e. single as opposed to mixed), does not only affect the AEV, but also plays a prominent role in affecting the ease of water flow in unsaturated soil (see both the parameters *a* and *n* in Table 5; $p$-value <0·001).

In Fig. 4(b), the best-fitted SHCFs of the four cases are compared with the predicted ones based on the best-fitted SWRC and $k_s$ using the van Genuchten (1980) equation. Not surprisingly, the best-fitted and predicted $k_r$ values for the bare soil are only slightly different. However, evidently, for tree- and grass-only cases, the predicted reduction rate of $k_r$ is greater than the best-fitted one. On the contrary, for mixed tree–grass soil, the predicted reduction rate of $k_r$ is less than the best-fitted case. Comparison of the results in Tables 4 and 5 reveals that, for a given vegetated condition, the fitted parameters for the SWRC are not always the same as those for the SHCF. This implies that the presence of plant roots changed the soil pore size and its distribution, which are the fundamental properties that govern soil water retention and hydraulic conductivity (Scholl *et al.*, 2014; Ng *et al.*, 2016b). Indeed, most existing predictive equations of the SHCF, including that suggested by van Genuchten (1980; equations (1) and (2)), do not take into account the root effects on the changes of soil pore size distribution and hence soil hydraulic properties. Based on the comparison in Figs 4(a) and 4(b), it may be important to link both the parameters *a* and *n* in the van Genuchten (1980) equation, or an equivalent parameter that describes the reduction rate of $k_r$ in other prediction equations, with root trait(s).

## CONCLUDING REMARKS

This study has used the instantaneous profile method to quantify the effects of plant roots on unsaturated hydraulic properties of vegetated silty sand, under single- and mixed-species planting conditions. The water retention ability of both the tree-only and grass-only soils was greater than that of the bare soil. Although there was no discernible difference in terms of the rate of water desorption, the air-entry value of the silty sand increased substantially due to the presence of roots. However, under mixed-species planting where root decay was found, vegetated soil showed an evident reduction of the air-entry value. Compared with the bare soil, soils planted with single species showed reduced saturated hydraulic conductivity, whereas soils with mixed-species planting showed an increase due to preferential flow through soil macro-pores associated with root decay. Prediction of SHCF based on the known SWRC using an existing equation works well for bare soil, but there are discrepancies with measurements for all vegetated soil cases, either planted with single or mixed species. The rate of reduction of hydraulic conductivity is substantially over-estimated for the tree- and grass-only cases, but is under-estimated for the mixed planting case.

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## NOTATION

- $a$ fitting parameter in van Genuchten's equation (van Genuchten, 1980)
- $k$ soil hydraulic conductivity
- $k_r$ relative soil hydraulic conductivity
- $k_s$ saturated hydraulic conductivity
- $m$ fitting parameter in van Genuchten's equation (van Genuchten, 1980)
- $n$ fitting parameter in van Genuchten's equation (van Genuchten, 1980)
- $R_v$ root volume ratio
- $s$ matric suction
- $S_r$ degree of saturation of soil

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